U.S. Department of Labor

Mine Safety and Health Administration
Pittsburgh Safety & Health Technology Center
P.O. Box 18233
Pittsburgh, PA 15236

Mine Waste and Geotechnical Engineering Division

February 12, 2007

MEMORANDUM FOR IRVING McCRAE
Contracting Officer, Acquisition Management Division
MSHA - Headquarters, Arlington

THROUGH: STANLEY J. MICHALEK
Acting Chief, Mine Waste and Geotechnical Engineering Division

FROM: STEVEN J. VAMOSSY
Civil Engineer, Mine Waste and Geotechnical Engineering Division

For GEORGE H. GARDNER
Senior Civil Engineer, Mine Waste and Geotechnical Engineering Division

SUBJECT: Summary of the Geophysical Void Detection Demonstration Projects - Crosshole Seismic Tomography, Borehole Radar, and Crosshole Radar Tomography Conducted by Colorado School of Mines, MSHA Account Number B2532537, Edgar Experimental Mine, Idaho Springs, Colorado

Colorado School of Mines (CSM) has recently fulfilled a contract to demonstrate crosshole seismic tomography, borehole radar, and crosshole radar tomography technologies for detecting underground mine voids. The demonstration project was conducted at the Edgar Experimental Mine in Idaho Springs, Colorado. We are the Contract Officer's Technical Representative's (COTRs) for this project. The purpose of this memo is to provide a general summary of the completed project and discuss the results.

BACKGROUND

CSM was the prime contractor for this demonstration project. Blackhawk, a division of Zapata Engineering (Blackhawk), was subcontracted to conduct the crosshole seismic tomography survey. Geo-Recovery Systems, Incorporated, was subcontracted to assist in carrying out the borehole and crosshole radar field surveys.

The Edgar Mine is an old silver mine which has been operated by CSM since 1921. It is used extensively for research and training activities. Testing for this project was being performed around a tunnel at this mine which was originally developed as part of the United States Army, Korean Tunnel Detection Program. An overview map is shown in Figure 1. The particular tunnel used for this demonstration is referred to as "The Army North Drift Tunnel." The tunnel varies in shape but its average dimensions are approximately 11 feet by 11 feet. It is extensively bolted in the roof and ribs. It has been precisely surveyed, is well characterized, and is surrounded by a number of existing boreholes.

Testing of both geophysical methods was performed between two existing boreholes designated as U1 and U5. These boreholes are located 35.45 feet apart on each side of the tunnel. Borehole U5 is approximately 10 inches in diameter and is located to the southwest of the tunnel. It extends to a depth of more than 300 feet. Borehole U1 is approximately 6 inches in diameter, is located to the northeast of the tunnel, and is approximately 286 feet deep. The top of the casing of borehole U5 is approximately 5.38 feet higher in elevation than that of borehole U1. The tunnel is approximately 206 feet deep. Both boreholes are cased at the top through the soil and weathered rock, but are uncased through rock over the survey interval. As part of the project, a bulkhead was constructed in this tunnel in order to create a water-filled mine void for later testing.

After CSM was awarded the contract, a project kick-off meeting was held on December 14, 2004, to introduce the team members and to develop a process for reporting project milestones and invoicing for progress payments. The field work and data acquisition was then completed as follows: crosshole seismic and radar testing for air-filled void condition from September 21-23, 2005; and crosshole seismic and radar testing for water-filled void condition from October 1-3, 2005. We were on-site for the air-filled void tests, and our District representative, Mr. Jerry Kissell, Mine Safety and Health Specialist, Metal and Nonmetal Rocky Mountain District, was on-site for the water-filled void tests. The crosshole seismic tests were later repeated in January 2006 using the same procedure with a different seismic source. CSM then completed the field data processing and developed a draft project report.

CSM had originally divided their draft report into two parts. Part 1 of the draft report included the background information along with the crosshole seismic results. Part 2 of the draft report included only the borehole and crosshole radar results. CSM submitted Part 1 of the draft report on August 9, 2006, and Part 2 of the draft report on September 14, 2006. The format and content of the Part 2 report was found to be unacceptable, and we requested that CSM submit a revised report. A revised Part 2 report was submitted on October 6, 2006. Following the receipt of each draft report, copies were disseminated to the Peer Review team members for feedback. Comments from the team members were then collected and forwarded to CSM to be addressed. On January 30, 2007, an electronic copy of the final report from CSM was received in this office, followed by hard copies of the report received via overnight mail on January 31, 2007. Based on our review of the final report, we have found that the comments from the Peer Review of the draft report were adequately addressed.

DEMONSTRATION OF CROSSHOLE SEISMIC METHOD

Blackhawk conducted the crosshole seismic survey. The survey data was collected by pairing a seismic source in borehole U1 and a string of receivers (hydrophones) in borehole U5 to generate and capture seismic signals transmitted between the source and receiver boreholes. An Etrema electronic source was used to generate seismic energy in the source borehole. The source generated a frequency sweep from 60 to 1000 Hertz. The hydrophone string consisted of 12 Oyo hydrophones with a fixed spacing of 3 feet. Seismic data was recorded on a Geometrics R24 Strata View, 24-channel seismograph. The source and hydrophone string depths were measured by attaching a fiberglass tape measure to each string.

To provide acoustic coupling for the test equipment, the boreholes were filled completely with water. Due to the fractured subsurface, the boreholes experienced some water loss. However, the tests could still be performed as long as the water level in the holes was greater than the highest elevation of the surveyed zone. The water levels were checked periodically and the boreholes were refilled as necessary.

The hydrophone string and Etrema source were lowered down the boreholes and the seismic data was collected with the source and receivers in various positions to provide optimum seismic raypath coverage. Specifically, the first test started with the source and receiver at a depth of 280 feet. The source was then raised and activated every 3 feet to a location 50 feet above the mine void. At that time, the hydrophone string was raised 36 feet and the source was lowered back below the elevation of the mine void and a second test was performed. In total, five series of seismic tests were conducted (i.e. the hydrophone string was raised four times, 36 feet per raise). The entire sequence of testing was later repeated when the void was completely filled with water.

Discussion of Results

Blackhawk also performed the data processing. The recorded seismic signals were filtered to enhance the usable seismic signals within the frequency range of the source. Filtering is a technique used to eliminate background noise from other sources recorded by the seismograph and enhance the desired signal. After reviewing the data and an initial attempt at processing the data, it was determined that recorded signals were dominated by electronic cross-feed of the signal sent to drive the source, and the data was not of sufficient quality to process. Specifically, the arrival times for the first seismic waves to travel from the source to the receiver could not be determined. The Etrema source was identified as the cause of the cross-feed problem. Therefore, the surveys were repeated in January 2006, using a sparker seismic source. The sparker source generated data of much greater quality. Blackhawk claims that a sparker source was their first choice for these tests; however, none were available during the initial field tests. These repeated tests were conducted at no extra cost to MSHA.

The data was processed using a tomography software package called GeotomCG. Low velocity anomalies from the data are usually interpreted as voids or as fractured, loose rock zones within the rock mass. For the air-filled condition, the void was interpreted to be about 8 feet above the actual void elevation (Figure 2). For the water-filled condition, the void was interpreted to be about 3 feet above the actual void elevation (Figure 3). CSM explained that the vertical offsets may be due to the irregular shape of the void or due to fractures around the void walls. There may also be a small error in the measured depth of the source and receiver string. It is possible the tape measure could have slid slightly along the source and receiver cables. The water-filled void condition produced more accurate results. This may be due to less attenuation of the signal propagating through the rock strata surrounding the water-filled void than the air-filled void. Also, the presence of water in the rock fractures surrounding the void, due to water seepage, may have improved the signal to noise ratio and resulted in better tomographic inversions.

DEMONSTRATION OF BOREHOLE AND CROSSHOLE RADAR METHOD

Geo-Recovery Systems assisted in the data acquisition phase for the radar surveys. A RAMAC/GPR control system from Mala GeoSciences was employed for these tests. The equipment consisted of one hundred megahertz (100MHz) pulse-type transmitter and receiver antennas, each enclosed in watertight fiberglass casings and each wired with 300 feet of fiber-optic cable. The data was digitally recorded on a laptop computer. A computer controlled winch with a digital depth encoder was used to move and measure the transmitter and receiver positions. The borehole surveys were first conducted in borehole U1 by coupling the antennas together. The transmitter was located on bottom and the receiver was located on the top. The signal was monitored as the assembly was lowered down the borehole.

Following completion of the borehole survey, crosshole tests were conducted by lowering the transmitter antenna into borehole U5 and the receiver antenna into borehole U1. The antennas were simultaneously pulled up the boreholes while signals to the receiver were measured over a 200 foot interval. These tests were repeated for 5, 10, -5, and -10 meter constant offsets between the transmitter and receiver. Unfortunately, the winch and digital depth encoder failed during this test, so the antenna cables had to be moved by hand and the depths were recorded from markings made periodically upon the cables. The entire sequence of testing was later repeated after the void was completely filled with water.

Discussion of Results

The borehole survey data was processed using the GRORADAR software package. The characteristic signature of a void in the processed data usually appears as a diffraction pattern shaped like a hyperbola. The peak of the hyperbola occurs when the antenna is closest to the void. The interpreted data indicated that the center of the void was about 195 feet below the surface of Borehole U1, which corresponds to elevation 7884 feet (Figure 4). As a comparison, the true center of the void is located at approximate elevation 7874 feet. To determine the distance between the borehole and the void, the two-way travel time can be converted to distance, using velocity. The two-way travel time corresponds to the time required for the radar pulse to travel to the reflector (air-filled void) and back. For this data set, the distance of the void from the borehole was calculated to be 10 feet, which is close to the actual distance of approximately 12 feet. The borehole survey data from the water-filled void condition showed almost identical results in terms of the void location (Figure 5), thus the presence of water did not have much effect on the results of this method. Although the location of void could be identified in the record (knowing its position beforehand), there were a number of hyperbolic features that looked similar to the one representing the void, with a subtle difference in the radius of curvature being the distinguishing feature of the tunnel.

The crosshole radar method requires more significant data processing and interpretation using tomography inversion. This data processing was performed under the direction of Professor Gary Olhoeft, Colorado School of Mines. Professor Olhoeft has used software algorithms in the past to process and model data from the U.S. Army Korean Tunnel Detection Program. Unfortunately, Dr. Ohloeft concluded that the data acquired for this project was not suitable for tomography inversion. Tomography inversion requires that all five transmitter-receiver offsets have sufficient anomaly amplitude and dynamic range to proceed with tomographic processing and modeling. Neither the air-filled and water-filled void data produced these anomalies in all five offsets. In three offsets that did have adequate anomalies (indicating the presence of a void) (Figure 6), there were errors in depth which CSM attributed to the depth encoder failure. The crosshole radar was, in three other cases, successful in indicating the presence of a void and the correct depth, but the location between the boreholes could not be identified due to insufficient data points.

Professor Olhoeft claims that he had better success in the past using the PEMSS II hole-to-hole radar system, which was specifically designed for the Korean Tunnel Detection Program. He indicates that the PEMSS II system has much more power and higher system dynamic range, better antenna patterns, and better antenna-ground coupling than the RAMAC system used for this project. Additional data is included in the report substantiating this claim. Unfortunately, the PEMSS II system has not been manufactured in years and is no longer available.

CONCLUSION

The project yielded mixed results. The conditions of the demonstration were highly idealized (i.e. detecting a large void at a very short distance). The interpreted void was as much as 8 feet off the actual void elevation with boreholes only approximately 12 feet away from the void. While an 8-foot discrepancy may be tolerable under many conditions, it is not known whether this would increase significantly with distance. CSM could not comment on whether they would expect better results if the boreholes were spaced further apart or if the offset error would be proportional.

The Peer Review team members also provided mixed opinions of the results. Dr. Robert Nigbor indicated that "the results of the void detection attempts in a well-controlled rock zone using crosshole seismic tomography were surprisingly poor." A Peer reviewer from the U.S. Army Corps of Engineers stated that "the borehole radar survey was successful in detecting both the air-filled and water-filled void." Another Peer reviewer felt that "the results of this work are inconclusive and should not be taken as reference for future attempts to appraise the value of radar techniques in locating subsurface voids."

In summary, CSM had limited success in detecting mine voids with the crosshole seismic tomography method and the borehole radar method. The crosshole radar method successfully identified voids and, in some cases, was able to determine an accurate depth, but insufficient useable data was collected to locate the void between the boreholes.

If you have any questions, please contact me.

Attachment

cc: T. Hoch - Chief, PSHTC
P. Retzer - TS

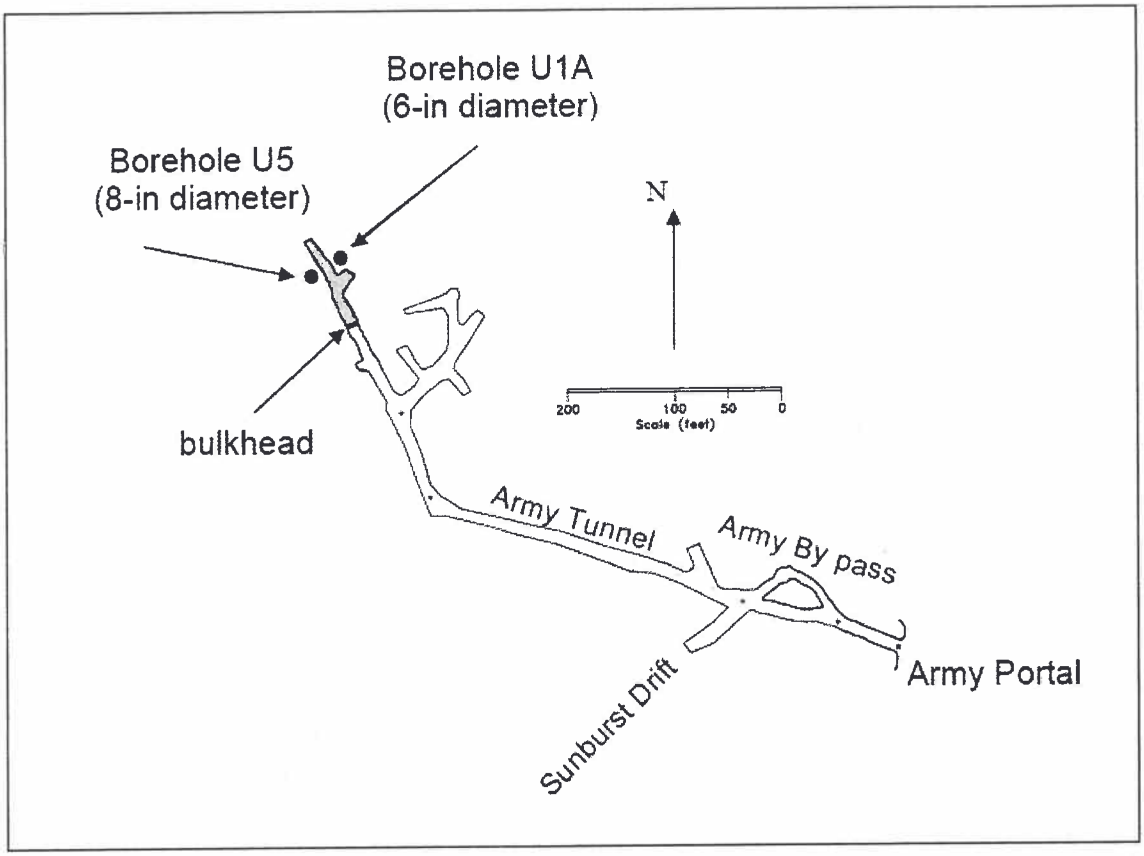

Figure 1: Overview of the Army North Drift Tunnel at the Edgar Experimental Mine. Note location of bulkhead and boreholes U5 and U1.

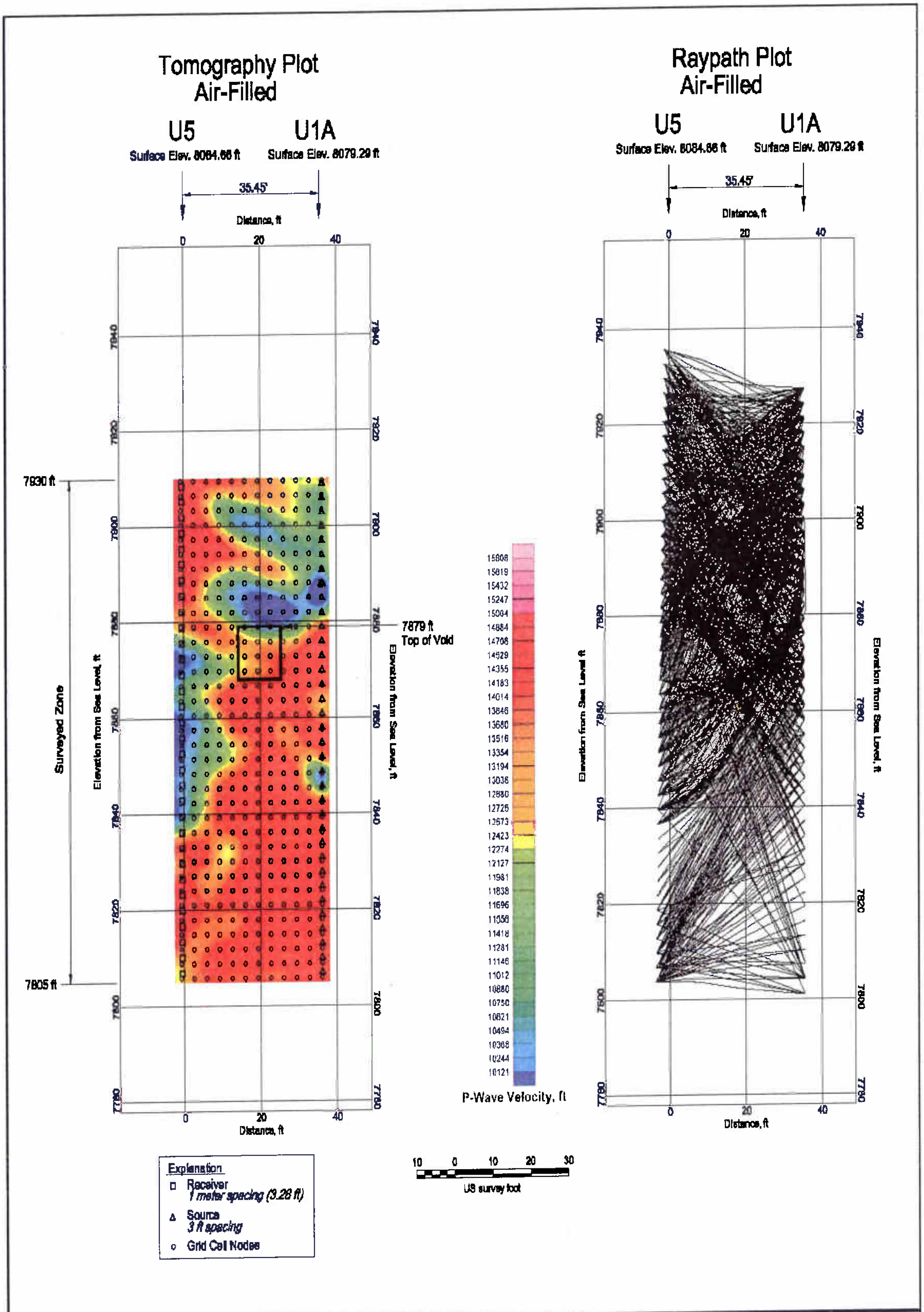

Figure 2: Two-dimensional crosshole seismic tomogram image for the air-filled void condition.

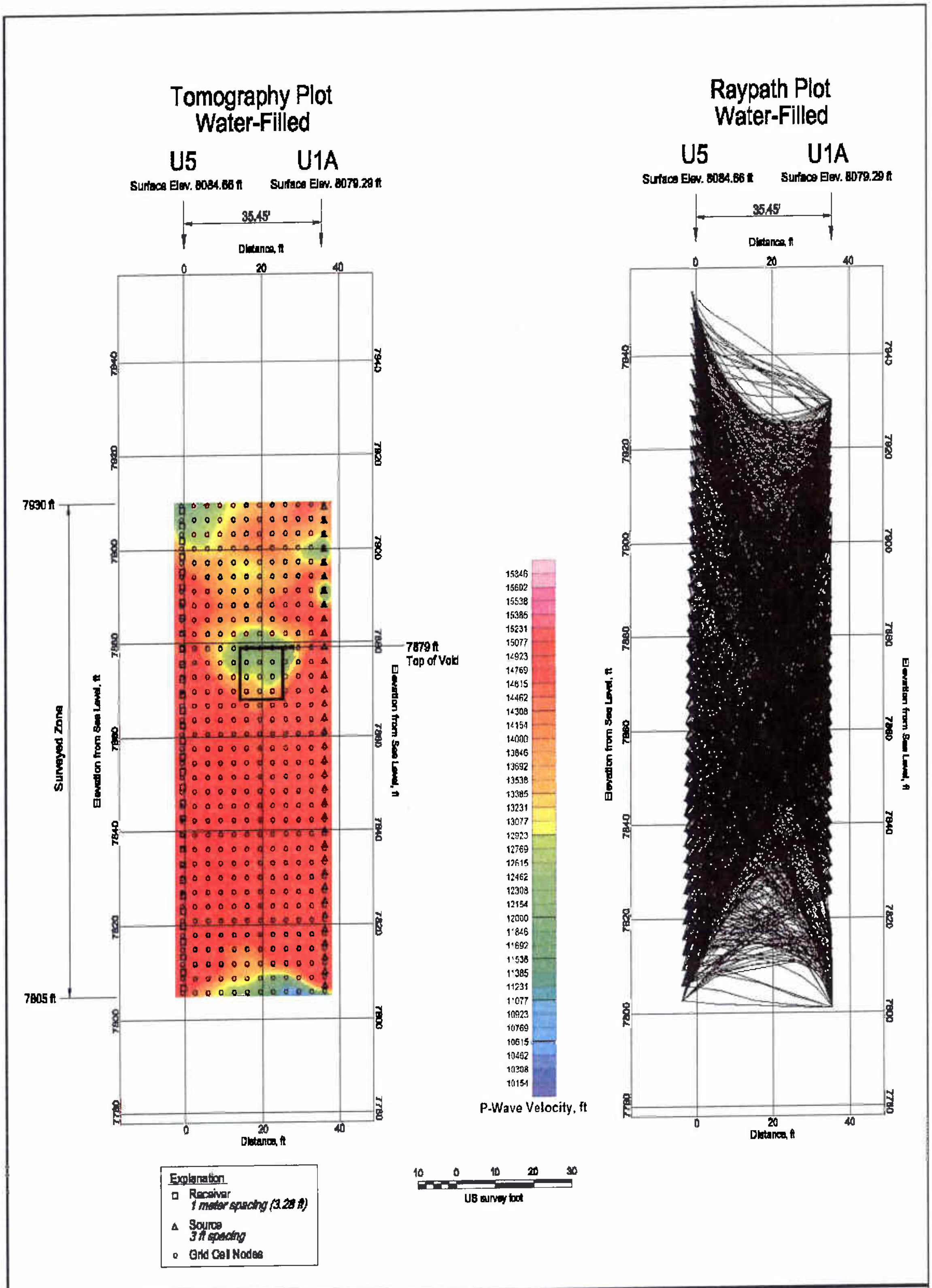

Figure 3: Two-dimensional crosshole seismic tomogram image for the water-filled void condition.

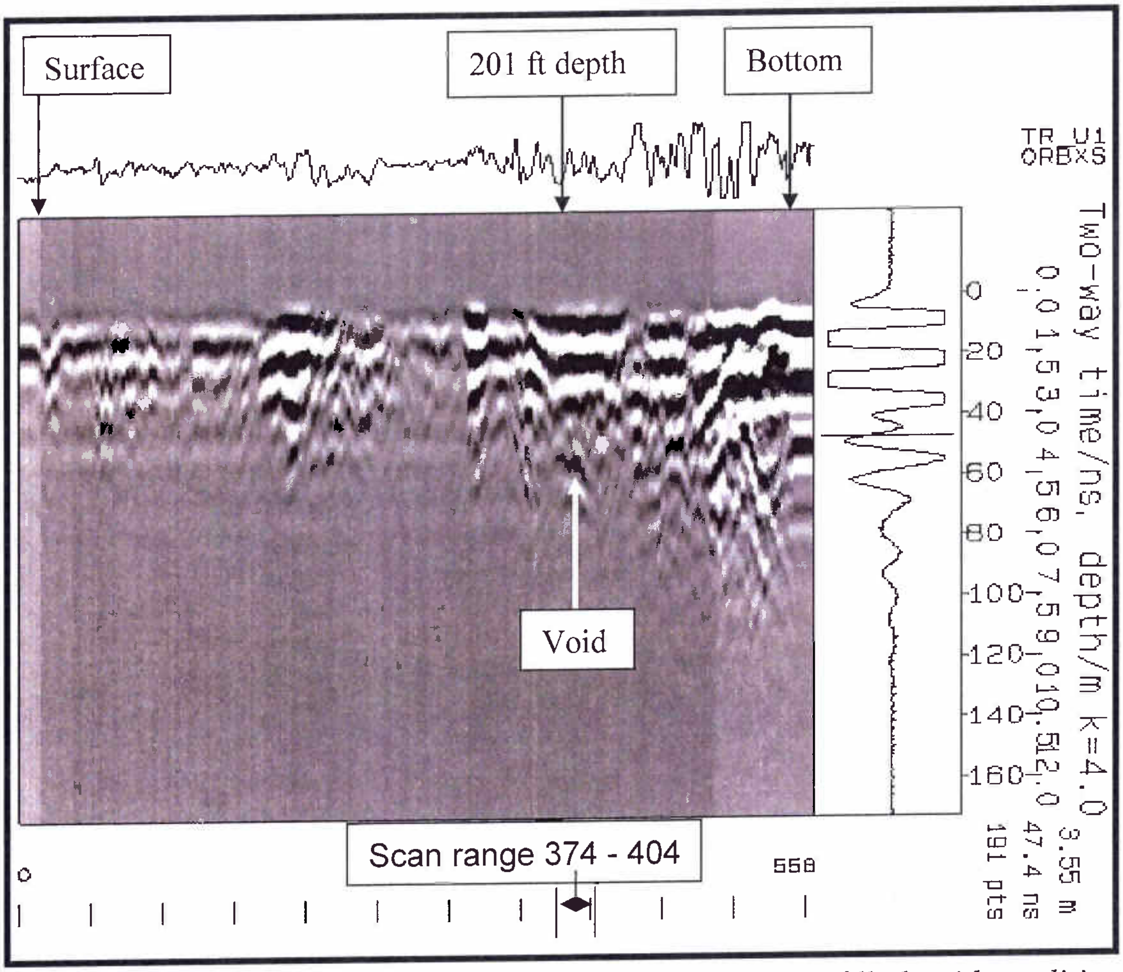

Figure 4: Borehole radar data from Borehole U1 for the air-filled void condition.

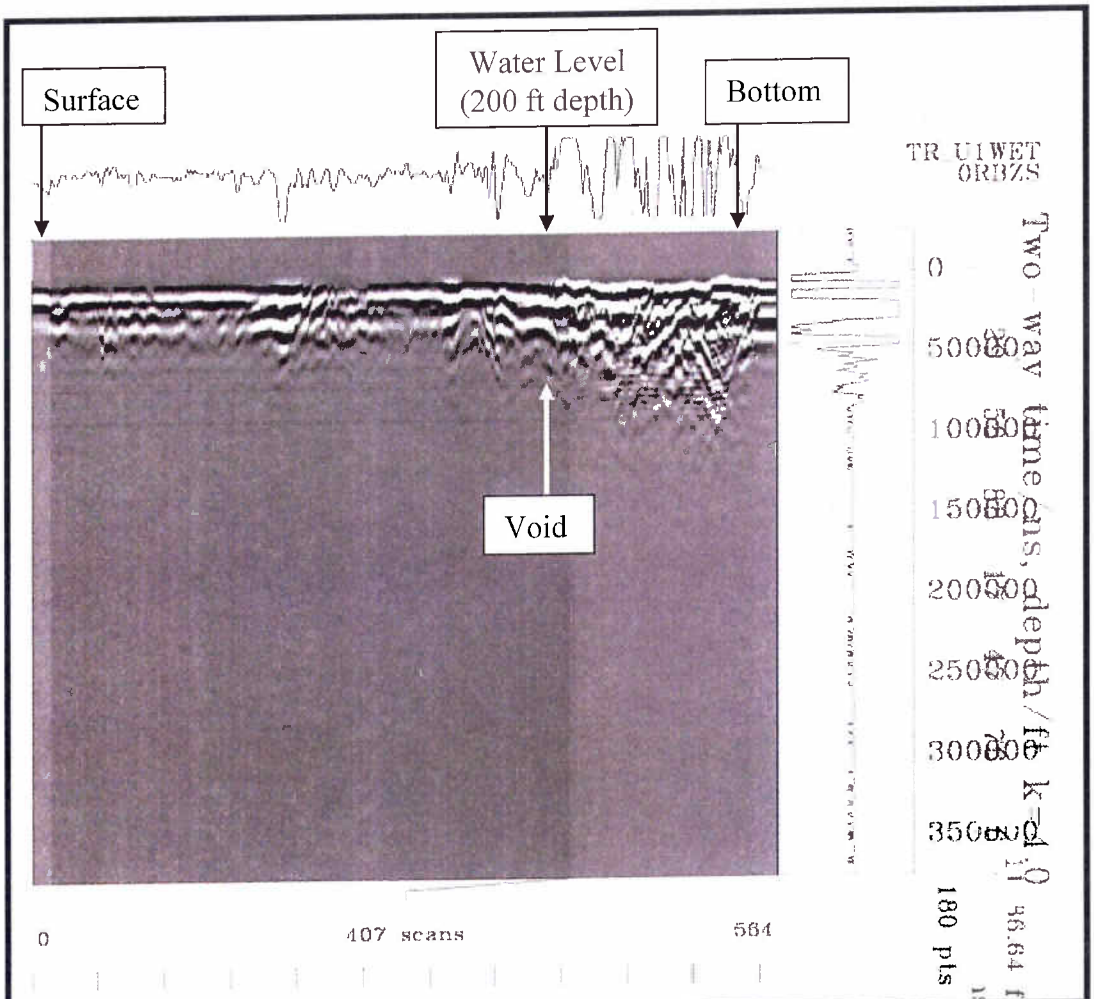

Figure 5: Borehole (U1) radar data for the water-filled void condition.

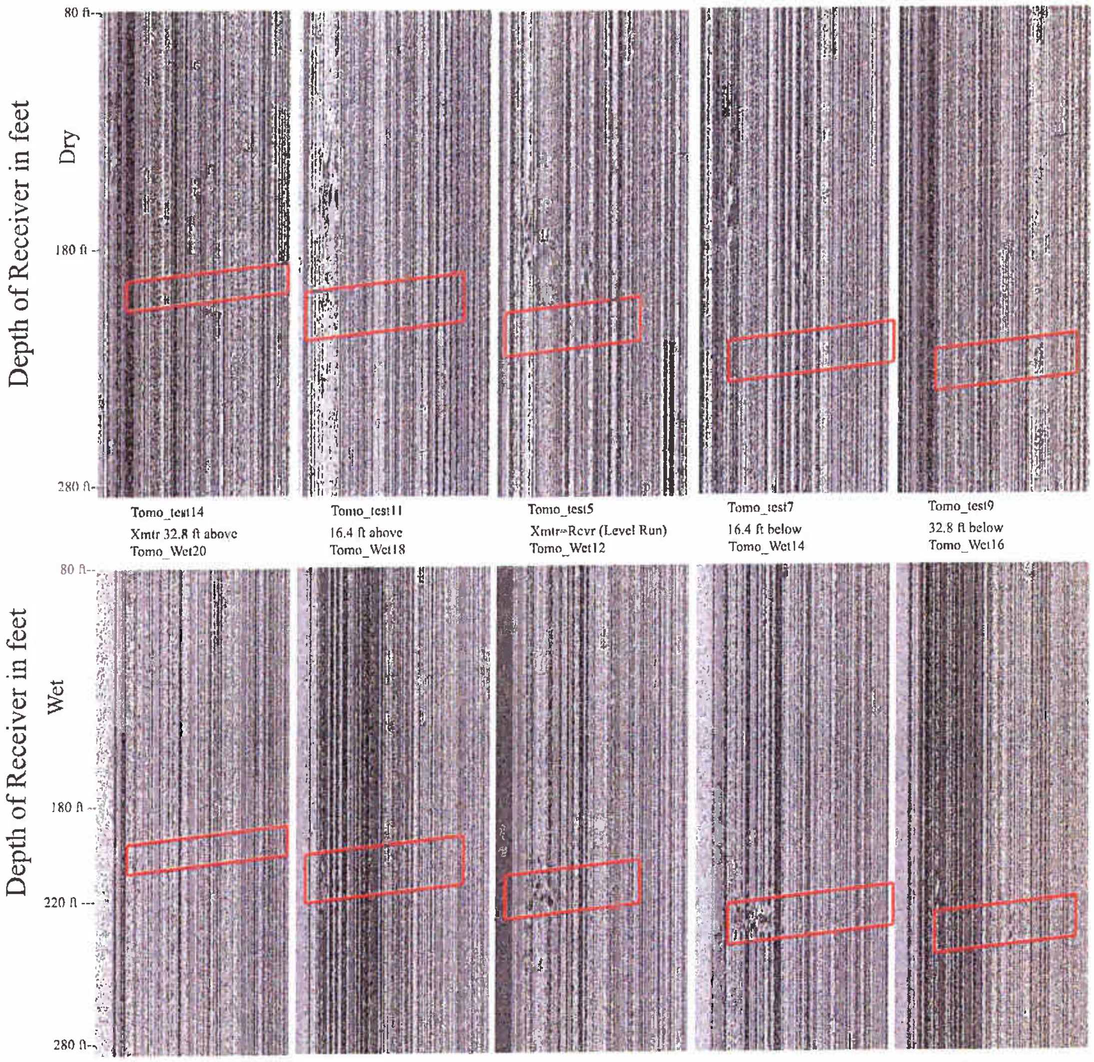

Figure 6: Crosshole radar data for each of the five offsets. The upper data set is for the air-filled void condition, and the lower data set is for the water-filled void condition. The red boxes indicate the expected location of the void.